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Potential of coastal armour units as energy dissipators to enhance the characteristics of hydraulic jumps

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ABSTRACT

Energy dissipating structures are strategically positioned at the base of dam spillways to prevent riverbed erosion and safeguard downstream infrastructures. The objective of this study is to experimentally explore the potential of a novel approach involving the use of coastal structures, known as armour units, as energy dissipators. Two armor unit models were designed using AutoCAD by adopting the geometry of a wave and tetrapod, and subsequently fabricated using a 3D printer with polyactic acid (PLA) material. Using a HM 160 Hydraulic Flume, experiments were performed by simulating discharge over short-crested weir, with a sloped spillway, and generating hydraulic jumps over the armour units that were installed downstream. Inflow conditions of the jumps ranged from a Froude value (Fr1) of 1.7 to 4.0. It was observed that both the wave and tripod structures induced a ski-jump effect before the hydraulic jump, which would facilitate the transportation of sediments and minimize scour risks in practical applications. Additionally, the energy dissipation level through the jumps had improved by four-fold as the height of the ski-jump doubled. Both structures also caused a significant reduction in sequent depth and length of the hydraulic jumps, up to 40% and 50%, respectively, as compared to the classical hydraulic jump formation on a smooth bed, which may lead to a more cost-effective basin design. Overall, the findings of this research highlights the possibility of utilizing a minimal number of units for adequate energy dissipation, offering significant advantages in scenarios where mitigating flood energy in open channels is required.

1. INTRODUCTION

Hydraulic jumps are known to occur in open channels when a high velocity and shallow water flow, known as supercritical flow, abruptly changes its flow depth and pressure into subcritical flow. This can be caused by, for example, a sudden change in the channel slope, an obstacle in the flow path, or a distinct change in the bed roughness (Chanson, 2004). While hydraulic jumps have various applications in engineering and fluid dynamics, including water management, irrigation, and flood control, one of its primary applications is for energy dissipation at the base of dam spillways (Laishram, 2022). The United States Bureau of Reclamation (USBR) type basin is one of the most common types of hydraulic structures used at the base of dams and generally consists of a long rectangular stilling basin with various appurtenances known as energy dissipators, such as sills, cascades and baffle blocks, designed to facilitate the hydraulic jump. The critical function of the energy dissipators is to control the hydraulic jump and dissipate the excess kinetic energy associated with the supercritical flow at the base of the spillway, particularly subsequent to flood events, thereby preventing erosion of the channel bed, local scouring, and damage to downstream of structures (Ghoveisi, 2016). Energy dissipators also serve to prevent sedimentation in the channel (Kuriqi et al., 2020). However, there are several issues inherent with traditional dissipators that still need to be overcome, such as the balance between energy dissipation and sediment management, scour and erosion risks, as well as economic and environmental impacts (Bhate et al., 2021). Recent studies have devoted considerable efforts to address these issues, primarily through experimenting with alternate types of dissipators.

Parsamehr et al. (2022) showed that a basin consisting of sixteen rows of lozenge-shaped elements, with 6-7 elements per row, was an effective energy dissipator and in controlling hydraulic jumps over an adverse slope (Figure 1). The arrangement of staggered rows of elements also led to a reduction in sequent depth with increasing adversity in slope. Lozenge type dissipators have also been employed to examine hydraulic jumps occurring in a gradually expanding rectangular stilling basin by Hassanpour et al. (2017), where it was found that sequent depth had decreased with increasing expansion ratio of the basin. Gandhi and Singh (2014) showed that a similar result could be achieved, for the case of a suddenly expanding basin, with a more economic design involving only 3 trapezoidal shaped baffles and a shallow end sill positioned downstream of the baffles. Nikmehr and Aminpour (2020) generated hydraulic jumps over a simulated rough bed by using 22 evenly distributed trapezoidal-shaped sills that were strategically positioned along a lowered basin, aligning the crest of the sills with the original bed level. The findings revealed that as the bed roughness increased, there was a decrease in jump length and an increase in the rate of energy dissipation, and effect that was primarily attributed to the heightened turbulence generated by the roughened bed. Another study by Matooq and Taleb (2018) that experimented with configurations ranging from eight to twelve rows of prismatic elements, with 5 elements per row, along the channel bed found that, while the variation in intensity of elements did not significantly effect the energy dissipation, slight changes in the dimensional parameters of the elements did have a notable effect.

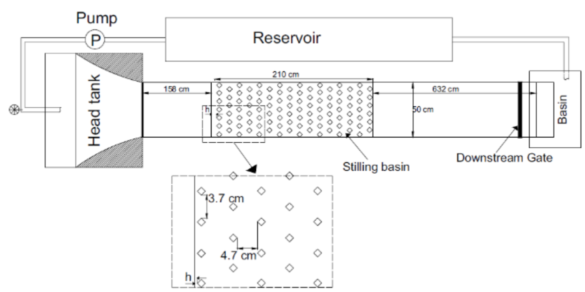

Figure 1: Lozenge-shape elements laid along the stilling basin (Parsamehr et al., 2022).

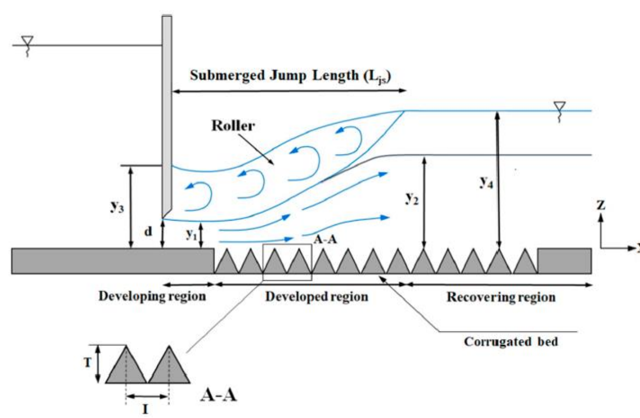

Figure 2: Rough bed simulated using triangular corrugations (Ghaderi et al., 2021).

Ghaderi et al. (2021) investigated submerged hydraulic jumps formed over a basin composed of macrosized triangular corrugations (Figure 2), where it was deduced that the roughness from the corrugations created additional turbulence and eddies, resulting in higher energy dissipation rates through the hydraulic jump. Similarly, Dasineh et al. (2021) studied submerged hydraulic jumps over triangular corrugated bed through computational fluid dynamic (CFD) techniques, and found that the Froude number had the greatest effect on the submerge depth ratio. Gu et al. (2019) applied the smoothed particle hydrodynamics (SPH) method to computationally model hydraulic jumps over a bed composed of sinusoidal-shaped corrugations, and discovered that a clockwise vortex formed in the hydraulic jump area, which expanded with increasing Froude number and was capable of dissipating 10% more energy as compared to the case of a smooth bed.

Rajaratnam and Hurtig (2000) was one of the first to conduct experiments using a screen-type energy dissipator, with about 40% porosity and in single and double layers. The study found that the location and spacing of the screens played a critical role in determining the energy dissipation rate, with the best results obtained when the screens were located immediately downstream of the jump and spaced at a distance equal to the jump length. Abbaspour et al. (2019) then explored the potential of utilizing porous screens, with 50% porosity and single/double layered, on beds with adverse slopes. It was shown that the energy dissipation had increased with increasing adversity of the slope, and that double screens were more effective in energy dissipation than single screens. Singh and Roy (2023) further employed triple layer screens with 45% porosity and mixed shape openings (circular, square and triangular) to analyze hydraulic jumps (Figure 3), and found that for Froude values greater than 13 it is possible to achieve higher energy dissipations compared to the previous screen arrangements.

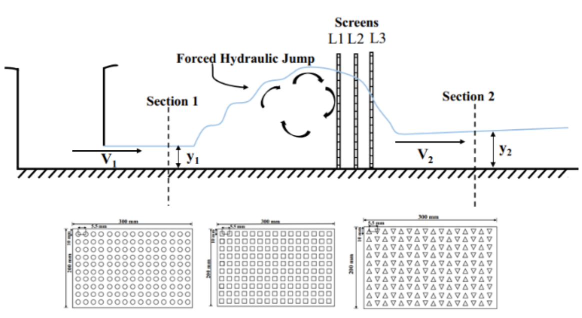

Figure 3: Triple layer screens with various shape openings (Singh and Roy, 2023).

Another intriguing category of energy dissipating structures are breakwater armour units (Figure 4), which are specifically designed to dissipate the immense energy carried by tidal waves along a coast (Smith, 2016). Numerous studies have demonstrated the capacity of various types of armoured structures for energy dissipation in coastal applications, including: steep block ramps armoured with stagger boulders (Ahmad et al., 2009); triple rubble-mound layer consisting of a fine, medium and large size gravel (Cao et al., 2021); double rubble-mound layer composed of double armor layer of concrete cubes and a permeable core of fine gravel (Clavero et al., 2020); partially perforated-wall caisson breakwaters (Lee et al., 2023). Recent investigations have also indicated that such armored units could serve as energy dissipators in open channels. The specific designs of such armour units enhances the bed roughness and disperses the incoming flow jet in a way such that the sequent depth and jump length of hydraulic jumps are shortened, thereby reducing the design costs of the basin (Attashi et al., 2020). Despite these encouraging findings, it is worth noting that further research and attention in this area are still required to fully explore its potential and applicability.

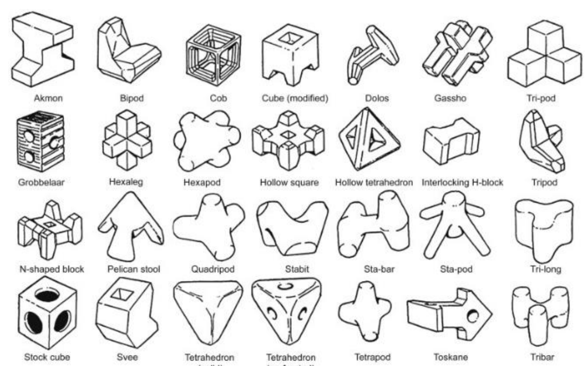

Figure 4: Types of breakwater armour units used in coastal applications (Smith, 2016).

The primary goal of this study is to experimentally explore the potential of employing breakwater armor units, typically utilized in coastal settings, as energy dissipators at the base of dam spillways. All experiments were conducted in a HM 160 Hydraulic Flume, with a channel cross-section measuring 86 × 300 mm. To simulate discharge down a spillway, a sloped short-crested weir was positioned downstream of the intake reservoir. Two types of armour units were designed herein using AutoCAD, based on the geometry of a wave and tetrapod, respectively, with dimensions appropriate for the channel. The structures were fabricated by a state-of-the-art 3D printer from polyactic acid (PLA) material, which is a biodegradable plastic. The armour units were then installed in the flume downstream of the weir in a single row arrangement consisting of only four units. Several flow simulations were carried out in the flume, and subsequently the effects of the wave and tetrapod structures on the characteristics of the hydraulic jumps were studied. This research hopes to demonstrate that the use of armour units could potentially allow for a more efficient, economic and sustainable basin design at the base of dam spillways. This is in contrast to traditional stilling basins that often incorporate excessive appurtenances, incurring higher costs and posing ecological challenges by impeding aquatic mobility and increasing the risk of direct structural impact.

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2. MATERIALS AND DESIGN

2.1. Hydraulic flume

All experimental simulations were conducted using a HM 160 Experimental Flume in the Fluid Mechanics laboratory of the Military Technological College, Sultanate of Oman, under a controlled environment and at room temperature. The flume consists of a 2.5m long open channel with a 86 × 300 mm cross-section and a 280 L water tank capacity. The channel walls are composed of transparent tempered glass and the bed is of smooth stainless steel. The water flow through the channel is powered by a 0.75 kW pump, capable of reaching a maximum a flow rate of 15 m3/h and a maximum head of 21 m. An illustration of the apparatus is described in Figure 5.

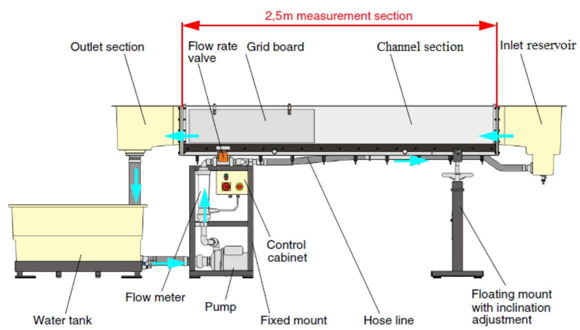

Figure 5: Components of the HM 160 Hydraulic Flume.

2.2. Design of short-crested weir

The simulation of discharge down a sloped spillway was achieved by employing a short-crested weir (Figure 6). The weir was constructed with a body consisting of film-faced plywood, and a 1 mm aluminium lining along the crest and downstream slopes. To prevent undesired water leakage along the channel walls, rubber sealant flaps were affixed to the sides of the weir. Chute blocks were also incorporated at the base of the weir to safeguard against corrosion, stabilize the structure, and enhance hydraulic jump performance. The design of the structure was specifically customized with the aim of optimizing the weir's hydraulic efficiency. The trapezoidal geometry of the weir, characterized by sloped upstream and downstream faces, as well as a sloped crest, offers several practical advantages. The upstream slope effectively prevents the accumulation of silt from reaching the crest (Obaida and Mohammed, 2023). The sloping downstream face minimizes cavitation concerns at high flow rates and improves the sensitivity to downstream submergence ratios (Nourani et al., 2021). Furthermore, a positively sloped weir crest is known to enhance the coefficient of discharge (Daneshfaraz et al., 2020).

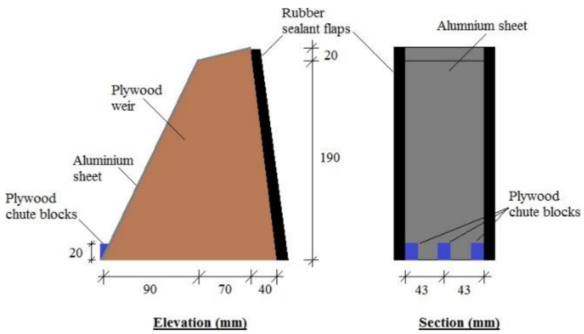

Figure 6: Design of the short-crested weir (not to scale).

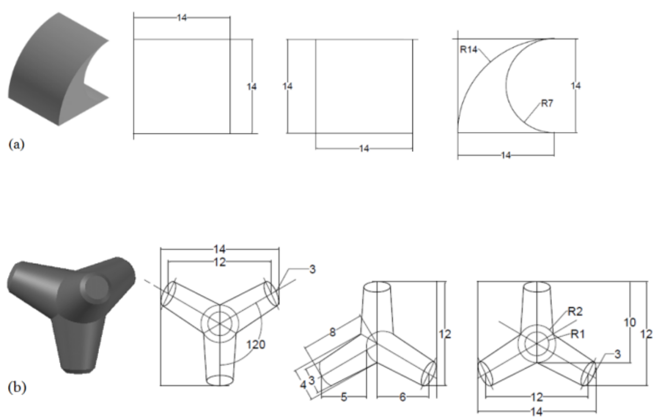

Figure 7: Design of the armour unit structures: (a) wave and (b) tetrapod

2.3. Design of armour unit structures

Two distinct armour unit structures, resembling a wave and tetrapod shape, were designed with the aid of the AutoCAD program (Figure 7). The geometric configurations of the structures were based on previous research findings, while its dimensions were selected based on the ratio of proportionality between the dimensions of the armor units and of the channel section. The physical structures were fabricated using a 3D printer, specifically the Makerbot Replicator Z18, to a dimensional accuracy of ± 0.2 mm. The material used in printing was polylactic acid (PLA), which is a lightweight plastic and a biodegradable material. A total of 24 units of each type of armor units (wave and tripod) were printed. Following the printing, the units were cleaned of impurities using a 120 grit sandpaper, ensuring a smooth and even surface.

3. EXPERIMENTATION

3.1. Layout and inflow conditions

The configuration and layout of the various hydraulic structures positioned along the channel is illustrated in Figure 8. The weir was installed in the channel at a distance of 20 cm from the inlet reservoir section. To create the basin for the armor units (wave and tetrapod), a 20 cm thin plastic panel was affixed to the channel bed using silicone at a location 8 cm downstream of the weir. Each armour unit was attached to the panel in rows of four by silicone, as specified in Figure 8. Further, the position of the armour units was varied by shifting them downstream along five different rows. A tailgate was also installed at the end of the channel, which could be raised or lowered in order to vary the flow velocity and discharge, and hence allow the observation of different hydraulic jump regimes. For each row of armour units, a total of 14 flow simulations were conducted by incrementally increasing the flow rate from 4 to 11 m3/h, resulted in a range of inflow Froude (Fr1) values between 1.7 and 4.0.

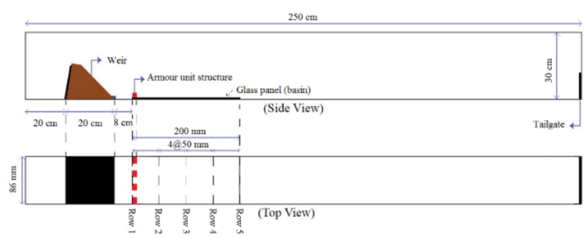

Figure 8: Layout of the hydraulic structures in the open channel (not to scale).

3.2. Measurements and analysis

Figure 9 depicts the formation of a hydraulic jump in the channel. To enhance the visualization of water movement within the hydraulic jump and to facilitate the identification of specific flow structures such as roller vortices, eddies, and recirculation zones, blue dye was introduced into the flow. As indicated in the figure, the supercritical depth (y1) and subcritical depth (y2), i.e. the vertical distances from the base of the channel bed to the water surface, were measured to an accuracy of 0.1 mm using a Vernier point gauge positioned along the centerline of the channel section. Similarly, the height of the ski-jump created by the armor units above the channel bed (h) was measured. The total length of the jump (Lj) was determined as the horizontal distance from the toe of the jump to the flow section downstream where the water surface appeared level and undisturbed. Additionally, the distance between the toe of the weir and the toe of the jump (Ls) was recorded. The inflow Froude number (Fr1) and

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energy dissipation through the jump (ΔE) were subsequently calculated:

$$Fr_1 = \frac{q}{y_1\sqrt{gy_1}} \quad (1)$$

$$\Delta E = E_1 - E_2 = \left(y_1 + \frac{q^2}{2gy_1^2}\right) - \left(y_2 + \frac{q^2}{2gy_2^2}\right) \quad (2)$$

where q is the discharge per unit width of the channel, and E_1 and E_2 are the specific energies upstream and downstream of the jump, respectively.

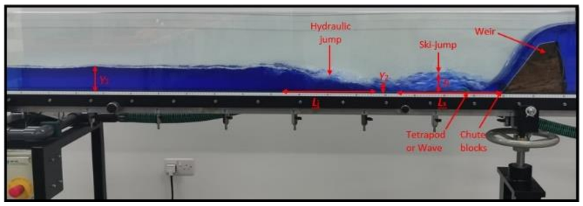

Figure 9: Parameters measured along the hydraulic jump.

The phenomenon of the classical hydraulic jump (CHJ) occurring downstream of a sluice gate in a smooth, horizontal rectangular channel has been extensively investigated in numerous renowned historical studies spanning the past century (Belanger, 1841; Hager, 1992; Chow, 1959). Table 1 lists the expressions defining the characteristics of the CHJ as a function of the inflow Froude number (Fr1).

TABLE 1. CHARACTERISTICS OF THE CLASSICAL HYDRAULIC JUMP (CHJ)

Reference	Characteristic	Formulation
Belanger (1841)	Sequent depth	$\frac{y_2}{y_1} = 0.5\left(\sqrt{1+8Fr_1^2} - 1\right)$
Hager (1992)	Jump length	$\frac{L_j}{y_1} = 220\tanh\left[(Fr_1 - 1)/22\right]$
Chow (1959)	Energy dissipation	$\frac{\Delta E}{E_1} = \frac{\left(-3+\sqrt{1+8Fr_1^2}\right)^3}{\left[8\left(-1+\sqrt{1+8Fr_1^2}\right)\left(2+Fr_1^2\right)\right]}$

4. RESULTS AND DISCUSSIONS

Various characteristics of the hydraulic jumps are studied in this chapter. Results are compared with the classical hydraulic jump (CHJ) formulations, as specified in Table 1. In addition, the findings are analyzed in relation recent studies exploring alternative energy dissipators. These include Elsebaie and Shabayek (2010) and Ahmed et al. (2014), who studied hydraulic jumps using corrugated aprons in the basin. Ghandi and Singh (2014) employed a combination of baffle blocks and an end sill to generate hydraulic jumps. Sadeghfam et al. (2014) experimented with single and double perforated screens with 40% porosity positioned downstream of a sluice gate. Elaswad et al. (2022) further examined the effect of screens on suddenly expanding basin. Jafar (2016) designed a flow portioning structure increase the friction resistance effect on the hydraulic jump.

4.1. Sequent depth ratio

The sequent depth ratio (y2/y1) is one of the key parameters that is both an indication of how much energy is dissipated through the hydraulic jump and the intensity of turbulence and mixing. Excessive turbulence can disrupt aquatic habitats and impact the movement of fish and other aquatic species. Figures 10 and 11 display the results of y2/y1 against varying inflow Froude number (Fr1). For both the wave and tetrapod structure, the relationship between y2/y1 and Fr1 appears to be linear. The corresponding linear equations are shown in Table 2.

When the wave armour structure was positioned in rows 1-4, the sequent depth ratios exhibited minimal variation, with the corresponding data clustered tightly together. At row 5, however, the sequent depths were considerably higher. Similarly, for the tetrapod structure, the y2/y1 values corresponding to rows 2-5 were closely aligned, while the values for row 1 were lower. Furthermore, the results of the wave structure at row 5 and tetrapod structure at rows 2-5 agree well with the findings of Gandhi and Singh (2014) and Elsebaie and Shabayek (2010). Interestingly, these structural configurations lead to a significant reduction in the sequent depth compared to the CHJ and Jafar (2016) approach, suggesting the potential for a more cost-effective basin design

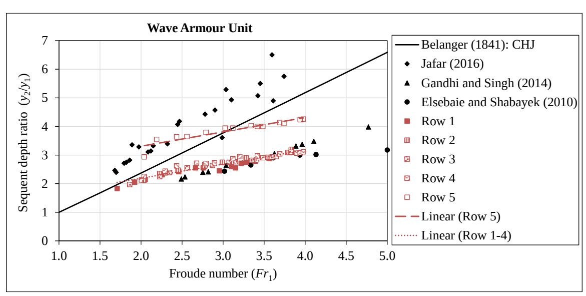

Figure 10: Sequent depth ratios of the jumps resulting from the wave armour unit.

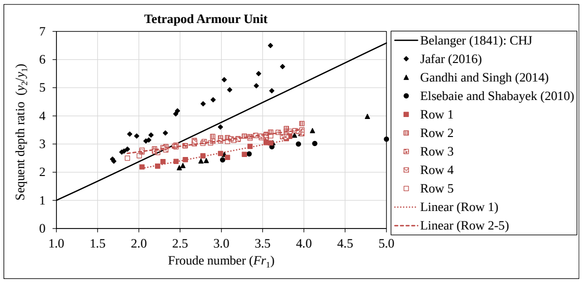

Figure 11: Sequent depth ratios of the jumps resulting from the tetrapod armour unit.

TABLE 2. SEQUENT DEPTH RATIO AS A FUNCTION OF INFLOW FROUDE NUMBER

Function: $y_2/y_1 = a + b \cdot Fr_1$: ($1.5 \leq Fr_1 \leq 4.0$)				Statistic
Armour unit	Row	a	b	R^2
Wave	1-4	0.4930	1.2036	0.91
	5	0.5006	2.3081	0.85
Tetrapod	1	0.5731	0.9676	0.93
	2-5	0.3975	1.9267	0.91

4.2. Relative jump length

The relative hydraulic jump length (Lj/y1) is a critical parameter that is used to optimize the design and operation of hydraulic structures such as spillways, weirs, and stilling basins. Short jumps can help reduce the erosive potential of fast-flowing water, protecting downstream infrastructure, and reduce the possibility of transporting sediments downstream. In agricultural and irrigation systems, however, long jumps, however, can promote more uniform flow conditions downstream, where even water distribution is essential for crop health. Figures 12 and 13 illustrate the variation of Lj/y1 measured against Fr1 for the wave and tetrapod armour units, respectively. Again, the trend between the two parameters in the figures seems linear, with the corresponding equations given in Table 3.

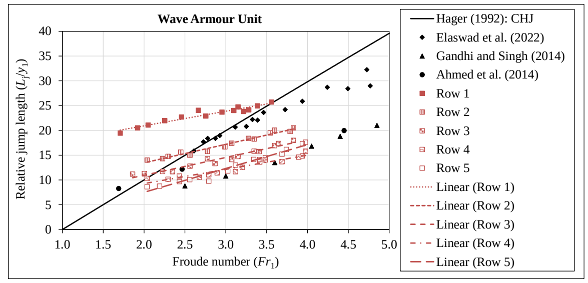

Figure 12: Relative jump lengths resulting from the wave armour unit.

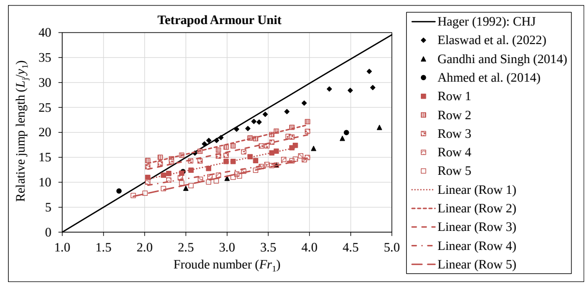

Figure 13: Relative jump lengths resulting from the tetrapod armour unit.

Unlike the sequent depth pattern, the jump lengths were uniquely dependent on the position or row of the wave or tetrapod structure, as each row resulted in a different set of linear data. Further, for both structures the lowest jump lengths were produced at row 4, while the highest jump lengths corresponded to row 1 for the wave structure and row 2 for the tetrapod structure. This would suggest that positioning the structures near the end of the basin would be beneficial for reducing the jump length, thus leading to a more economical basin design. In addition, the jump lengths produced by the structures were substantially lower than that of the CHJ for smooth surface, which is further indicative of the effectiveness of the armour unit structures. Notably, the performance of these structures, especially at Rows 4 and 5, closely resembled that reported by Gandhi and Singh in (2014), further demonstrating that the armour units are comparable to other energy dissipation systems.

TABLE 3. RELATIVE JUMP LENGTH AS A FUNCTION OF INFLOW FROUDE NUMBER

Function: $L_j/y_1 = a + b \cdot Fr_1$: ($1.5 \leq Fr_1 \leq 4.0$)				Statistic
Armour unit	Row	a	b	R^2
Wave	1	2.9540	15.0040	0.93
	2	3.7340	5.9925	0.97
	3	3.5865	3.7750	0.96
	4	2.8706	3.5132	0.92
	5	4.8157	-2.1364	0.96
Tetrapod	1	3.5034	3.5088	0.97
	2	3.9771	5.6781	0.97
	3	3.5428	5.4064	0.95
	4	2.8050	3.6847	0.93
	5	3.5692	0.5234	0.97

5 3.5692 0.5234 0.97

4.3. Energy dissipation

Efficient energy dissipation systems are essential at the base of dam spillways to effectively dissipate a substantial portion of kinematic energy, thus preventing excessive turbulence and erosion downstream, which can be damaging to the environment and infrastructure. Figures 14 and 15 portrays the percentage of energy dissipation (ΔE/E1) % generated by the wave and tetrapod structures, respectively, as a function of the Fr1. Based on the data patterns, there it appears to be a non-linear relationship between ΔE/E1 and Fr1, which is further supported by the shape of the CHJ curve (Chow, 1959). The most optimum approximation to these relationships was established using the curve fitting tool in MATLAB, which yielded to be exponential in nature, as displayed in Table 4.

Given the close proximity of the data, it was apparent that one exponential equation adequately represented the results for Rows 1-4 of the wave structure, while another equation sufficed for Row 5. Similarly, for the tetrapod structure, a single equation proved sufficient for both Row 1 and Rows 2-5. This finding suggests that both structures effectively dissipated the highest energy when positioned in Row 1 and the lowest energy at Row 5. Furthermore, there was a considerable increase in the energy dissipation at Row 1 as compared to the CHJ, affirming the capacity of the structures. The results at Row 1 are also closely aligned with the outcomes of Sadeghfam et al. (2014), and performed better than that of the setup used in Elaswad et al. (2022) and Maatooq and Taleb (2018).

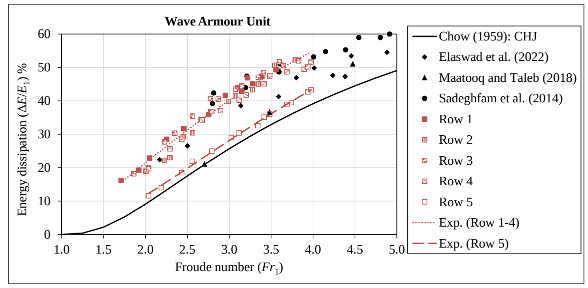

Figure 14: Energy dissipation through the jumps resulting from the wave armour unit.

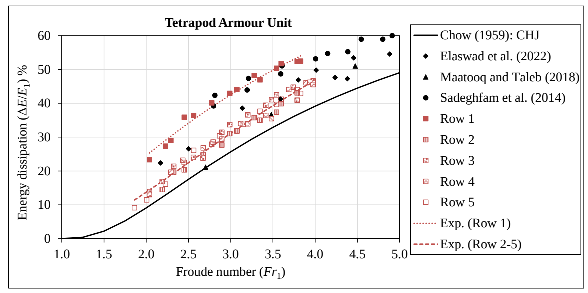

Figure 15: Energy dissipation through the jumps resulting from the tetrapod armour unit.

Function: $\Delta E/E_1 = a \cdot \exp(b/Fr_1)$: ($1.5 \leq Fr_1 \leq 4.0$)				Statistic
Armour unit	Row	a	b	R^2
Wave	1-4	$1.406(10)^2$	-3.762	0.83
	5	$1.625(10)^2$	-5.262	0.94
Tetrapod	1	$1.280(10)^2$	-3.305	0.90
	2-5	$1.599(10)^2$	-4.912	0.84

4.4. Location of the hydraulic jump

The hydraulic jump's position determines where the energy dissipation occurs. If the jump forms too far downstream, high-velocity water can cause severe erosion to the riverbed and nearby structures before the jump occurs. Accurate positioning helps ensure that the energy is dissipated where it's intended, minimizing erosion and protecting the riverbed and adjacent infrastructure. Figures 16 and 17 illustrate the relative position of the hydraulic jumps (Ls/y1) against the Froude number (Fr1).

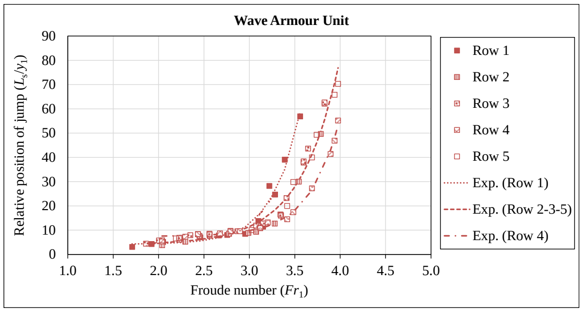

Figure 16: Location of the hydraulic jumps resulting from the wave armour unit.

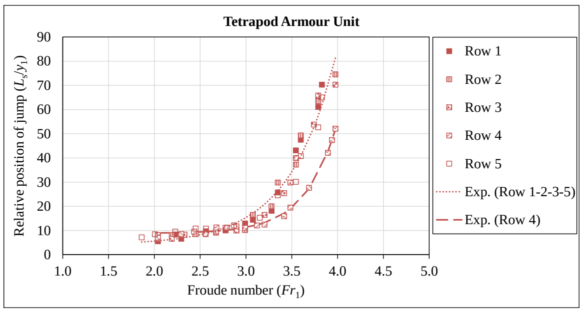

Figure 17: Location of the hydraulic jumps resulting from the tetrapod armour unit.

Some common trends can be observed for both the wave and tetrapod structures. Firstly, the relative position (Ls/y1) of the hydraulic jump increases rapidly as the Froude number (Fr1) increases from 1.5 to 4.0. The trend between these parameters appears to be exponential, as outlined in Table 5. Also, shifting the armour units downstream tends to increase the relative position of the hydraulic jump for the same Froude number, indicating a delayed formation of the jump. In general, the closer the armour unit structures are positioned to the upstream (i.e., Row 1), the further downstream the hydraulic jump initiates, and conversely, positioning the units further downstream causes the jump to start closer to the upstream section. This suggests that the initial flow remains supercritical for a longer distance before the energy is dissipated enough to form a hydraulic jump. When the units are placed upstream, they introduce an early disruption to the flow, but the flow retains enough energy to continue moving in a supercritical state for a longer distance. This results in a delayed formation of the hydraulic jump, which is observed as a further downstream position in the graphs

TABLE 5. Relative location of jump as a function of inflow Froude number

Function: L_s/y_1 = a·exp(b·Fr_1) + c : (1.5 ≤ Fr_1 ≤ 4.0)					**Statistic**
Armour unit	**Row**	**a**	**b**	**c**	**R^2**
Wave	1	$3.540(10)^{-4}$	3.356	4.201	0.92
	2-3-5	$6.430(10)^{-3}$	2.347	4.100	0.88
	4	$2.262(10)^{-4}$	3.073	7.434	0.93
Tetrapod	1-2-3-5	$3.068(10)^{-2}$	1.970	4.023	0.83
	4	$3.496(10)^{-4}$	2.948	8.838	0.94

4.5. Effect of the ski-jump on the energy dissipation

The ski-jump effect occurs as the supercritical flow encounters the armour units, causing the water to deflect upwards and create an airborne jet. This effect is critical as it changes the trajectory and velocity distribution of the flow, which in turn impacts the downstream hydraulic jump formation. The upward deflection of the flow reduces the direct impact of high-velocity water on the channel bed or downstream structures, which can significantly decrease the potential for scouring and erosion in the downstream area. The ski-jump effect can also help in mobilizing and transporting sediments downstream, preventing sediment accumulation near the base of the dam or spillway. Therefore, by reducing erosion and sediment buildup, the ski-jump effect can help maintain a more stable and natural riverbed downstream of the spillway, which is beneficial for aquatic ecosystems.

Figures 18 and 19 depicts the variation of the energy dissipation (ΔE/E1) % as a function of the relative ski-jump height (h/y1). Interestingly, both graphs demonstrate a positive correlation between the relative ski-jump height and the energy dissipation. As the ski-jump height increases relative to the inflow depth, the energy dissipation also increases. The linear trend lines for different rows indicate that the relationship between ΔE/E1 and h/y1 can be approximated by a linear function, as indicated in Table 6. For the wave structure, the energy dissipation is lower when the structures are placed in rows 1 and 2 compared to rows 3-5 for the same relative ski-jump height. This could indicate that positioning the armour units further downstream is more effective in dissipating energy. The converse is observed for the tetrapod structure, where rows 1-4 displayed higher energy dissipation than row 5. Overall, the graphs suggest that not only does the ski-jump height influence energy dissipation, but so does the position of the armour units.

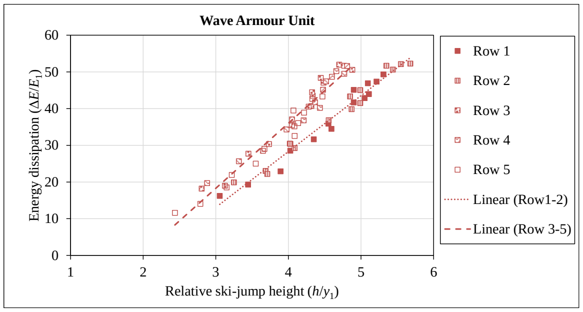

Figure 18: Relation between ski-jump and energy dissipation using the wave armour unit.

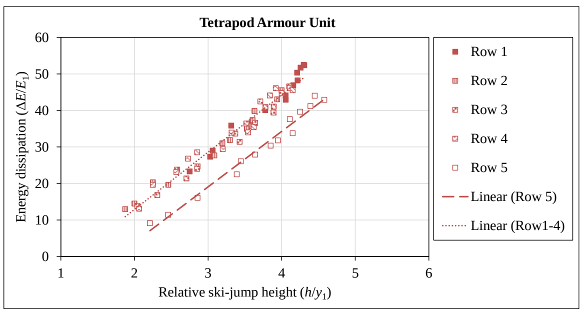

Figure 19: Relation between ski-jump and energy dissipation using the tetrapod armour unit.

TABLE 6. ENERGY DISSIPATION AS A FUNCTION OF SKI-JUMP HEIGHT

Function: $\Delta E/E_1 = a + b\cdot(h/y_1)$: $(2 \leq h/y_1 \leq 6)$				Statistic
Armour unit	Row	a	b	R^2
Wave	1-2	15.229	-32.613	0.97
	3-5	17.745	-34.967	0.95
Tetrapod	1-4	15.685	-18.469	0.97
	5	15.194	-26.521	0.98

5. DESIGN CONSIDERATIONS OF ARMOUR UNITS

The experimental findings and design considerations related to the wave and tetrapod armor units offer several insights into their practical application in real-world field settings, particularly in the design of stilling basins and other hydraulic structures. The distinct shapes of the wave and tetrapod units influence their performance. The wave structure, with its smoother, more streamlined design, may create more uniform flow conditions, while the tetrapod's complex geometry could enhance turbulence and energy dissipation. These characteristics should be considered when selecting the appropriate structure based on the specific hydraulic requirements.

The ability to manipulate the jump position and energy dissipation by altering the structure's shape or placement suggests that these designs could be tailored to specific field conditions. This customization can lead to optimized performance in varying flow regimes. By effectively managing energy dissipation and reducing downstream turbulence, these structures contribute to more sustainable hydraulic designs. This is important in protecting aquatic environments from the adverse effects of high-energy flows.

The reduction in hydraulic jump length and controlled turbulence could also influence sediment transport dynamics, which is critical in maintaining river and stream health. The observed reduction in sequent depth and jump length implies that stilling basins using these structures could be shorter and shallower, reducing the volume of materials required and overall construction costs. This makes them an attractive option for large-scale infrastructure projects.

6. CONCLUSIONS

Managing hydraulic jumps and dissipating energy effectively in hydraulic structures is a critical challenge in ensuring the longevity and stability of dams, spillways, and stilling basins. The improper handling of these aspects can lead to excessive turbulence, downstream erosion, and damage to infrastructure. This study aimed to address these challenges by evaluating the effectiveness of coastal armor unit structures in controlling hydraulic jumps, dissipating energy, and optimizing flow conditions within a stilling basin. After investigating two specific armour units, the wave and tetrapod structures, the key findings are summarized as follows:

• The use of wave and tetrapod structures results in a notable reduction in the sequent depth ratio, particularly when the units are placed upstream closer to the spillway. This reduction implies that the vertical space required in the stilling basin can be minimized, potentially lowering construction costs.

• The placement of wave and tetrapod armor units significantly influences the position of the hydraulic jump. Units positioned further upstream cause the jump to occur further downstream, while downstream placement leads to a shorter jump length within the basin.

• Both armor units effectively dissipate energy, with the highest dissipation observed when the structures are placed upstream. This demonstrates the potential of these units to prevent downstream erosion and protect infrastructure by reducing the kinetic energy of flowing water.

• The ski-jump effect, induced by the armor units, adds an additional layer of flow modification, enhancing energy dissipation before the main hydraulic jump. This effect is particularly beneficial in managing high-energy flows, reducing the risk of downstream damage.

• The relative jump length is closely tied to the row placement of the armor units. The lowest jump lengths are achieved when the units are positioned near the end of the basin, suggesting that such placement can lead to a more economical and efficient basin design.

While coastal armor units, have been widely used for coastal protection, their potential as energy dissipating structures in dam spillways remains largely unexplored. As this study shows, incorporating these units in spillway designs could offer substantial benefits, including enhanced energy dissipation, improved control over hydraulic jump location, and reduced downstream turbulence and erosion.

REFERENCES

Abbaspour, A., Taghavianpour, T., & Arvanaghi, H. (2019). Experimental study of the hydraulic jump on reverse bed with porous screens. Applied Water Science, 9, 1-7.

Ahmad, Z., Petappa, N. M., & Westrich, B. (2009). Energy dissipation on block ramps with staggered boulders. Journal of Hydraulic Engineering, 135(6), 522-526.

Ahmed, H. M. A., El Gendy, M., Mirdan, A. M. H., Ali, A. A. M., & Haleem, F. S. F. A. (2014). Effect of corrugated beds on characteristics of submerged hydraulic jump. Ain Shams Engineering Journal, 5(4), 1033-1042.

Atashi, V., Lim, Y. H., Khajavi, M., & Shafai-Bajestan, M. (2020, May). Characteristics of hydraulic jumps in stilling basins with permeable six-legged elements. In World Environmental and Water Resources Congress 2020 (pp. 65-75). Reston, VA: American Society of Civil Engineers.

Belanger, J. B. (1841). Notes sur I'Hydraulique. ("Notes on hydraulic engineering.") Ecole Royale des Ponts et Chaussees, Paris, France, session 1841-1842 (in French).

Bhate, R. R., Bhajantri, M. R., & Bhosekar, V. V. (2021). Future challenges in design of spillways and energy dissipators. ICOLD Symposium on Sustainable Development of Dams and River Basins, 24th-27th February, New Delhi.

Cao, D., Yuan, J., & Chen, H. (2021). Towards modelling wave-induced forces on an armour layer unit of rubble mound coastal revetments. Ocean Engineering, 239, 109811.

Chanson, H. (2004). Hydraulics of open channel flow. Elsevier.

Chow, V. T. (1959). Open channel hydraulics. McGraw-Hill, New York.

Clavero, M., Díaz-Carrasco, P., & Losada, M. Á. (2020). Bulk wave dissipation in the armor layer of slope rock and cube armored breakwaters. Journal of Marine Science and Engineering, 8(3), 152.

Daneshfaraz, R., Dasineh, M., Ghaderi, A., & Sadeghfam, S. (2020). Numerical modeling of hydraulic properties of sloped broad-crested weir. AUT Journal of Civil Engineering, 4(2), 229-240.

Dasineh, M., Ghaderi, A., Bagherzadeh, M., Ahmadi, M., & Kuriqi, A. (2021). Prediction of hydraulic jumps on a triangular bed roughness using numerical modeling and soft computing methods. Mathematics, 9(23), 3135.

Elaswad, S., Saleh, O. K., & Elnikhili, E. (2022). Performance of screen in a sudden expanding stilling basin under the effect of the submerged hydraulic jump. The Open Civil Engineering Journal, 16.

Elsebaie, I. H., & Shabayek, S. (2010). Formation of hydraulic jumps on corrugated beds. International Journal of Civil & Environmental Engineering IJCEE-IJENS, 10(1), 37-47.

Gandhi, S., & Singh, R. P. (2014, January). Hydraulic jump characteristics in non-prismatic channels. In ISHS 2014-Hydraulic Structures and Society-Engineering Challenges and Extremes: Proceedings of the 5th IAHR International Symposium on Hydraulic Structures (pp. 1-9). The University of Queensland.

Ghaderi, A., Dasineh, M., Aristodemo, F., & Aricò, C. (2021). Numerical simulations of the flow field of a submerged hydraulic jump over triangular macroroughnesses. Water, 13(5), 674.

Ghoveisi, H., Omid, M. H., & Kiker, G. A. (2016). Investigation of the effect of expansion angle on gradually expanding hydraulic jump in trapezoidal channel. Conference Proceedings.

Gu, S., Bo, F., Luo, M., Kazemi, E., Zhang, Y., & Wei, J. (2019). SPH simulation of hydraulic jump on corrugated riverbeds. Applied Sciences, 9(3), 436.

Hager, W. H. (1992). Energy dissipators & hydraulic jumps. Kluwer Academic Publication, Dordrecht, The Netherlands.

Hassanpour, N., Hosseinzadeh Dalir, A., Farsadizadeh, D., & Gualtieri, C. (2017). An experimental study of hydraulic jump in a gradually expanding rectangular stilling basin with roughened bed. Water, 9(12), 945.

Jafar, M. S. (2016). The friction resistance effect on the hydraulic jump location and energy dissipation, a laboratory study. Kufa Journal of Engineering, 7(2), 90-103.

Kuriqi, A., Koçileri, G., & Ardiçlioglu, M. (2020). Potential of Meyer-Peter and Müller approach for estimation of bed-load sediment transport under different hydraulic regimes. Modeling Earth Systems and Environment, 6(1), 129-137.

Laishram, K., Devi, T. T., Singh, N. R., & Kumar, P. A. (2022). Numerical and experimental study on energy dissipation in hydraulic jump: A comparison between horizontal and sloping rough channel bed. In Palermo, Ahmad, Crookston, and Erpicum (Eds.), Proceedings of the 9th IAHR International Symposium on Hydraulic Structures (pp. 1-10). IIT Roorkee, India. (DOI: 10.26077/cb4c-fdc3).

Lee, B. W., Baek, D., Ha, T., Lee, K. J., & Yoon, J. S. (2023). Experimental study on hydrodynamic performance of partially perforated-wall caisson breakwaters designed for the southeast coast of Korea. Journal of Coastal Research, 39(1), 167-174.

Maatooq, J., & Taleb, E. (2018). The performance of hydraulic jump over rough bed stilling basin consisting of cubic-shape elements. In MATEC Web of Conferences (Vol. 162, p. 03001). EDP Sciences.

Nikmehr, S., & Aminpour, Y. (2020). Numerical simulation of hydraulic jump over rough beds. Periodica Polytechnica Civil Engineering, 64(2), 396-407.

Nourani, B., Arvanaghi, H., & Salmasi, F. (2021). Effects of different configurations of sloping crests and upstream and downstream ramps on the discharge coefficient for broad-crested weirs. Journal of Hydrology, 603, 126940.

Obaida, A. A. M., & Mohammed, A. Y. (2023). The effect of Crump weir's geometry changes on hydraulic flow characteristics: A review. Proceedings of the 2nd International Conference on Scientific and Academic Research, March 14-16, 2023, Konya, Turkey.

Parsamehr, P., et al. (2022). Hydraulic jump over an adverse slope controlled by different roughness elements. Water Resources Management, 36(14), 5729-5749.

Rajaratnam, N., & Hurtig, K. I. (2000). Screen-type energy dissipator for hydraulic structures. Journal of Hydraulic Engineering, 126(4), 310-312.

Sadeghfam, S., Akhtari, A. A., Daneshfaraz, R., & Tayfur, G. (2014). Experimental investigation of screens as energy dissipaters in submerged hydraulic jump. Turkish Journal of Engineering & Environmental Sciences, 38, 126-138.

Singh, U. K., & Roy, P. (2023). Energy dissipation in hydraulic jumps using triple screen layers. Applied Water Science, 13(1), 17.

Smith, P. E. (2016). Types of marine concrete structures. In Marine Concrete Structures (pp. 17-64). Woodhead Publishing.